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# (54) Face-pumped laser with diffraction-limited output beam

(57) Diffraction-limited output beam quality is achieved with a laser having an elongated homogeneous active medium pumped through two optically plane, parallel faces 11, 12, and situated within a resonant cavity defined by a plane reflector 22 at one end and a concave spherical reflector 21 at the opposite end. For a ray of optical energy passing through the active medium, the effective optical length of the medium is greater in the plane of reflection than in a plane perpendicular to the plane of reflection and containing the ray, and separation between the reflectors is selected to form a stable resonator in the plane of reflection but unstable in the plane perpendicular to the plane of reflection and containing the ray.

Fig. 2.

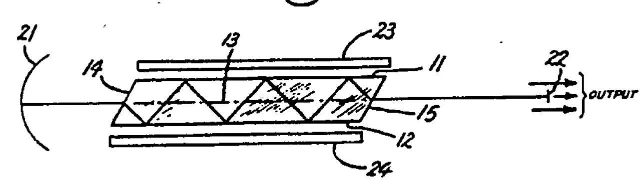


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Fig. 1.

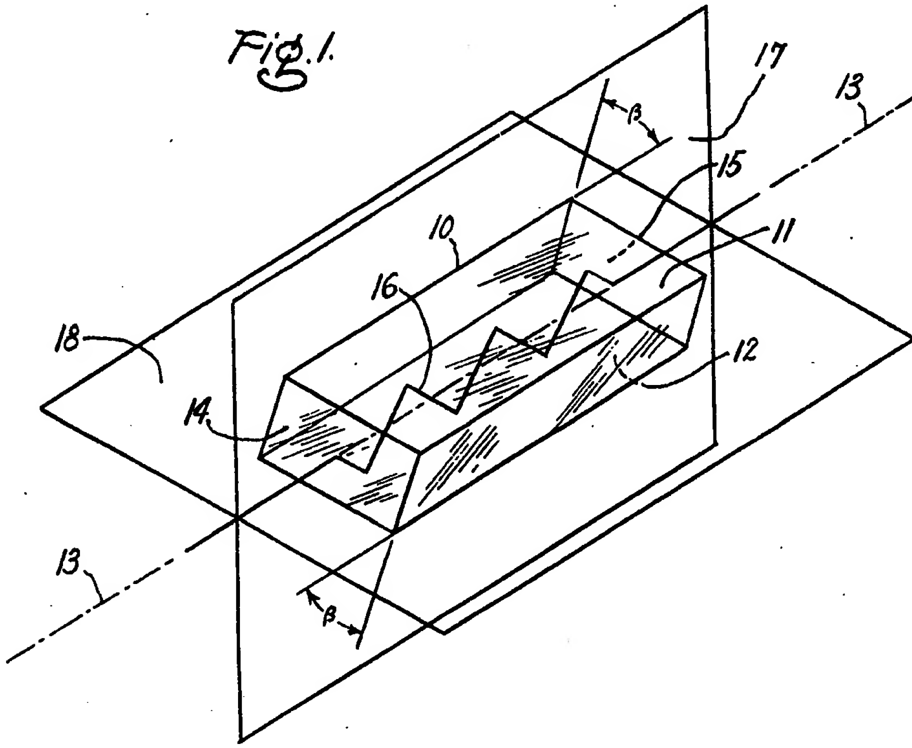
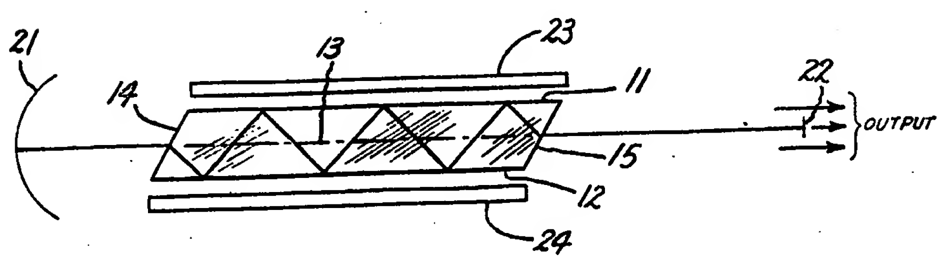



Fig. 2.



SPECIFICATION
**Face-pump d laser with diffraction-limited utput b am**

This invention relates to face-pumped lasers, and more particularly to a method and apparatus for producing a diffraction-limited output beam from a face-pumped laser cavity having a large Fresnel number.

Laser oscillations or propagations, to a certain extent are analogous to microwave cavity oscillations or propagations, such as in a waveguide. Both kinds of oscillations or propagations can be achieved in several modes, and the so-called lowest order transverse mode is usually favoured. In conventional optically-pumped rod lasers, thermal-optic distortions resulting from heating along with optical pumping are known to limit severely lowest order transverse mode operation. These distortions manifest themselves as a thermal lensing effect on the laser rod, due to the thermal gradient between the normally-cooled outer surface of the active medium and its relatively hot centre region, and as a depolarisation effect caused by stress distribution in the active medium which produces birefringence therein. While the thermal lensing effect on the laser rod can be approximately compensated, depolarisation cannot. As a result of the depolarisation effect, the lowest order transverse mode in the active medium cannot build up. Unless losses for the higher modes can be increased, the laser will therefore naturally oscillate in the higher order modes. Mode discrimination can be achieved simply by choosing the ratio of the cavity aperture size to cavity length sufficiently small (i.e. small cavity Fresnel number), but optical wavelengths are such that the required ratio is extremely small. As a result, either the active medium aperture must be small and the utilized volume of active material must be small, resulting in low efficiency, or, with a useful aperture size, the length of the cavity resonator must be so large as to be unwieldy. It is an object of the invention to provide simple means or apparatus for achieving mode discrimination without suffering low efficiency and without requiring a cavity resonator of excessive length, and which avoids thermal distortion problems. These problems are further explained in the subsequent description of Figure 1.

In accordance with the present invention there is provided a multiple reflection face-pumped laser for emitting a diffraction-limited output beam in a longitudinal direction, comprising; an elongated slab of homogeneous active laser medium having at least two optically plane faces extending substantially parallel to each other, the effective optical length of said active medium for a ray of optical energy passing therethrough being greater in the plane of reflection than in a plane perpendicular to said plane of reflection and containing said ray; pumping means for impinging electro-magnetic radiation upon at least one of said optically plane faces to excite atoms of said active medium to a metastable state so as to produce a population inversion therein; optically plane reflective means spaced from said active medium at one end thereof; and concave spherical reflective means spaced from said active medium at the opposite end thereof, said plane reflective means and said spherical reflective means defining opposite ends of a cavity resonant to optical energy passing through said active medium in a general direction parallel to said optically plane faces of said active medium and normal to the surface of said spherical reflective means at the point of impingement thereon, such that said cavity is stable in said plane of reflection but unstable in said plane perpendicular to the plane of reflection.

Briefly, in accordance with a preferred embodiment of the invention, a multiple reflection face-pumped laser for emitting a diffraction-limited output beam in a longitudinal direction comprises an elongated slab of homogeneous active medium having at least two longitudinally, optically plane faces extending substantially parallel to each other, the effective optical length of the active medium for a ray of optical energy passing therethrough being greater in the plane of reflection than in a plane perpendicular to the plane of reflection and containing the ray. Pumping means are provided for impinging electro-magnetic radiation upon at least one of the optically plane faces to excite atoms of the active medium to a metastable state, thereby producing a population inversion in the medium. The active medium is situated within a cavity resonant to optical energy passing through the active medium in a general direction parallel to the two optically plane faces of the active medium and defined by optically plane reflective means spaced from the active medium at one end thereof and concave spherical reflective means spaced from the active medium at the opposite end thereof, such that the cavity is stable in the plane of reflection but unstable in the plane perpendicular to the plane of reflection and containing the ray. The "stable/unstable" concept is further explained hereinafter. Optical energy emitted by the active medium in a general direction parallel to the two optically plane faces of the active medium is thus directed normal to the surface of the plane reflective means and normal to the surface of the spherical reflective means at the point of impingement thereon.

The invention will be better understood by reference to the following description taken in conjunction with the accompanying drawings in which:

Figure 1 is an isometric view of a fac -pumped laser active medium: and

Figure 2 is a schematic side vi w of a face-pumped laser employing the instant invention.

In Figure 1, a homogeneous active medium 10 of rectangular cross section, such as employed in W.S. Martin et al, United States patent 3,633,126, is illustrated. In one arrangement, the medium may comprise neodymium doped silicate

glass. Two optically plane faces 11 and 12 extend parallel to the longitudinal axis 13 of the body to produce a plurality of total internal reflections of a coherent beam of electromagnetic radiation illustrated by path 16. Two optically plane parallel end faces 14 and 15 at each longitudinal end of slab 10 of active medium are situated at Brewster's angle $\beta$ with respect to longitudinal axis 13 as measured in a plane 17 passing perpendicularly through faces 11 and 12 of laser active medium 10. Thus, each ray of coherent beam 16 is introduced into laser active medium 10 at an angle of incidence relative to longitudinally-directed faces 11 and 12 to refract the beam in plane 17 so as to impinge on face 11 or face 12 at an angle such that total internal reflection occurs at these faces. By total internal reflection from faces 11 and 12 alternately, the beam follows a zig-zag course in plane 17, and emerges by refraction from either of end faces 14 and 15 in a manner which causes the beam to coincide with longitudinal axis 13. Plane 17, which is the plane of reflection for ray 16 as it passes through medium 10 is known as the p-plane. Plane 18, which is perpendicular to plane 17 and also includes longitudinal axis 13, is known as the s-plane.

In a face-pumped laser active medium, such as slab 10, optical distortion occurs as the slab undergoes heating during its operation. Although this heating results essentially in no net distortion in p-plane 17, since slab 10 is well-compensated in the p-plane, distortion can result in s-plane 18 from pumping and heating non-uniformity across the width (i.e., the length of intersection of either of end faces 14 and 15 with plane 18) of slab 10. By fabricating the laser resonant cavity to favor strongly the lowest order transverse mode, it is possible to minimize or altogether eliminate this distortion.

One way of fabricating the laser resonant cavity to accomplish this result would be to employ an unstable resonator, i.e., a resonant cavity in which the radiation diverges as it passes between the cavity reflectors. At the output reflector of the cavity, output energy passes beyond the reflector perimeter because the beam cross section is wider than the reflector. The portion of the beam energy that is reflected from the output reflector for reamplification through the active medium can be geometrically selected so that only a uniphase wavefront is thus returned. For this reason, an unstable resonator can strongly select a uniphase wavefront in the resonant cavity making it possible to produce a diffraction limited output beam from a resonant cavity with a large Fresnel number. Unstable r sonators have be n discussed extensively in the prior art. See, for example, A.E. Siegman, *Applied Optics, 13,* 353-367 (February 1974).

A disadvantag of the unstable resonator is that fe dback from th output reflector cannot b more than about 10% if good m de c ntrol and stability are to b achieved. This requires that the gain through the activ medium be relatively high for laser oscillator operation. In common applications of face-pumped lasers, the active medium is in a solid host, is optically pumped and is of relatively low gain.

A resonator that is stable in the plane of low distortion and unstable in the plane in which there may be distortion makes effective use of the mode selectivity provided by the unstable resonator and, at the same time, allows relatively large (e.g. 50%) feedback from the output reflector. Moreover, the slab width (measured in plane 18) to thickness (measured in plane 17) ratio for a face-pumped laser of the type described herein is usually three or greater. This results in the intracavity aperture of slab 10 being relatively smaller in the plane of low distortion (yielding a small cavity Fresnel number) and larger in the plane with possible distortion (yielding a large cavity Fresnel number). For these reasons, a stable/unstable resonant cavity is well suited to use with a face-pumped laser of the type shown and described in the aforementioned United States patent 3,633,126.

A stable/unstable resonant cavity for a laser oscillator is readily implemented with a multiple reflection face-pumped laser slab in its conventional form, as shown in Figure 2, Thus slab 10, of rectangular cross-section, is fabricated with the beam entrance end faces 14 and 15 at the Brewster angle with respect to longitudinal axis 13. Active medium 10 is conventionally pumped through faces 11 and 12 by flashlamps 23 and 24, respectively, to excite atoms of the active medium to a metastable state and thereby produce a population inversion therein. The effective optical length of slab 10 in the p-plane (which contains the Brewster angle) is less than in the s-plane. Therefore by employing standard standard converging cavity optics including a concave spherical cavity reflector 21 and a plane output reflector 22, the separation between reflectors 21 and 22 can be adjusted so that the laser resonant cavity defined thereby is stable only in the p-plane and is unstable in the s-plane because the effective resonator length in the s-plane is greater than the length necessary for a stable resonant cavity.

In the special case of a concave spherical reflector 21 and plane output reflector 22, the separation of these reflectors is adjusted so that their optical separation in the p-plane is less than the radius of curvature of spherical reflector 21, and their optical separation in the s-plane is greater than the radius of curvature of the spherical reflector. This adjustment is easily accomplished since the optical length of the laser slab with the Brewster's angle end faces 14 and 15 is less in the p-plane than in the s-plane (by 41% of the slab length in the case of Nd:glass). The exact separation of the mirrors is adjusted so that the p-plane aperture of the slab is filled by optical energy in the lowest order stable resonator mode. The width of the output mirror (i.e., the s-plane dimension) is adjusted so that the s-plane apertur of the slab is filled by the optical energy in the unstable resonator mode. The reflectivity of

the output reflector may be adjusted to obtain optimium output efficiency. Cavity reflectors are not restricted to plane plus concave combinations; reflectors of a wide variety of curvatures may be employed so long as the criteria for the stable/unstable cavity are satisfied. Of course the curvature of the reflectors must be selected to yield the desired physical length of the resonant cavity, the desired Fresnel number in the p-plane, and the correct degree of instability in the s-plane.

The ends of the laser slab need not necessarily be at Brewster's angle, however. Other beam entrance angles can be used; nevertheless, Brewster's angle is often the most desirable because reflection losses are zero for p-plane polarized light passing through a surface at Brewster's angle. Thus the apparatus illustrated in Figure 2 provides a diffraction-limited output beam, directed longitudinally along axis 13, from a multiple reflection face-pumped laser by favoring the lowest order transverse mode therein, without any substantial sacrifice in output power.

The foregoing describes a face-pumped laser oscillator having a resonator which strongly favors the lowest order transverse mode. A diffraction-limited output beam is thus obtainable from a face-pumped laser resonant cavity being a large Fresnel number, the resonator being stable in the p-plane and unstable in the s-plane.

## CLAIMS

1. A multiple reflection face-pumped laser for emitting a defraction-limited output beam in a longitudinal direction, comprising:

an elongated slab of homogeneous active laser medium having at least two optically plane faces extending substantially parallel to each other, the effective optical length of said active medium for a ray of optical energy passing therethrough being greater in the plane of reflection than in a plane perpendicular to said plane of reflection and containing said ray;

pumping means for impinging electromagnetic radiation upon at least one of said optically plane faces to excite atoms of said active medium to a metastable state so as to produce a population inversion therein;

optically plane reflective means spaced from said active medium at one end thereof; and

concave spherical reflective means spaced from said active medium at the opposite end thereof,

said plane reflective means and said spherical reflective means defining opposite ends of a cavity resonant to optical energy passing through said active medium in a general direction parallel to said two optically plane faces of said active medium and normal to the surface of said spherical reflective means at the point of impingement thereon, such that said cavity is stable in said plane of reflection but unstable in said plane perpendicular to the plane of reflection.

2. A laser as claimed in claim 1 wherein said slab is of rectangular cross section.

3. A laser as claimed in claim 1 or 2 wherein said slab includes an end face at each longitudinal end thereof, each said end face being at the Brewster angle in said plane of reflection with respect to the longitudinal axis of said slab.

4. A laser as claimed in claim 1, 2 or 3, wherein said optically plane reflective means is of predetermined size, the spacing between said optically plane reflective means and said concave spherical reflective means being selected such that a portion of output energy of said laser passes beyond the perimeter of said plane reflective means.

5. A laser according to claim 1 and substantially as herein described with reference to Figure 2 of the accompanying drawings.

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